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Antarctic Climate Change and the Environment – 2015 Update

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Introduction

We provide an update on recent significant advances in our understanding of climate change across the Antarctic continent and the Southern Ocean, and the impact on the terrestrial and marine biota. It builds on the material included in the Antarctic Climate Change and the Environment (ACCE) report, which was published by SCAR in 2009 (Turner et al. 2009), with an update of the key points appearing in 2013 (Turner et al. 2013). At the request of the ATCM, SCAR agreed to provide regular updates on the original report (e.g. ATCM Resolution 4 (2010)) and this is coordinated by the SCAR ACCE Advisory Group. The scope of the group is to keep abreast of recent advances in climate science, with a particular focus on Antarctic climate change and the biological implications of such changes. A recent development has been that the original ACCE report and the updated key points have been made available online as a wiki at http://acce.scar.org/wiki/Antarctic_Climate_Change_and_the_Environment. This online version is being progressively updated by a number of editors with input from many active scientists.

Changes in the Antarctic physical environment

- Despite the appearance of stasis in global surface temperature, 2014 has been noted as marginally the warmest year on record. Fourteen of the 15 hottest years have now occurred since 1998, all but one of them in the 2000s. In the oceans, Argo data confirm that warming has continued at a rate of 0.4-0.6W/m^2 during 2006-2013 (Roemmich et al. 2015). Heat gain was divided equally between the 0-500 m and 500-2000 m depth layers. Most of the heat gain occurred in the Southern Hemisphere outside the tropics. The dominant role of the Southern Ocean in taking up additional anthropogenic heat and carbon was highlighted by Frölicher et al. (2015), who showed that "the Southern Ocean south of 30°S, occupying 30% of global surface ocean area, accounts for 43% ± 3% of anthropogenic CO_2 and 75% ± 22% of heat uptake by the ocean over the historical period."

- The climate of the Antarctic and Southern Ocean is more variable than those of lower latitudes because of the interactions between the atmosphere, ocean and ice. This makes the detection of a signal due to increasing greenhouse gas concentrations difficult (not least because of the complication added by the large signals resulting from the Antarctic ozone hole). Using climate model data from the third Coupled Model Intercomparison Project (CMIP3), Hawkins and Sutton (2012) estimated that in the Antarctic it could be several decades before a strong and unequivocal signal of greenhouse gas increase emerges from the large natural/intrinsic variability.

- Reconstructions of hemispheric climate for the past 1000 years (Neukom et al. 2014) confirm that the modern climate (post-1970) has been warmer than that in the Medieval Warm Period in both Hemispheres. While peak medieval warming in the Northern Hemisphere (1000-1100 AD) was offset from that in the Southern Hemisphere (1250-1350 AD), both Hemispheres experienced significant cooling at the heart of the Little Ice Age (1600-1700). The only other period when both Hemispheres have experienced the same change is the present warming since 1900. The difference in medieval times between the two Hemispheres suggests that internal processes (probably centred in the ocean) may have a significant role to play in controlling climate. External forcing (the Maunder Minimum in sunspots) may explain the synchronicity of the Little Ice Age signal between the Hemispheres.

- Based on the results of geochemical studies in snow pits and shallow cores, regional stack series of air temperature near Vostok station were obtained covering the last 350 years (Ekaykin et al., 2014). The comparison between this record and instrumental temperature data from Vostok station shows that winter temperature is mainly governed by variability of the Southern Annular Mode, while summer temperature is related to the Pacific Decadal Oscillation (PDO) and Southern Oscillation Index (a measure of the El Niño Southern Oscillation cycle). A change in the sign of correlation between Vostok climate record and Southern Hemisphere climatic indices is observed in the late 1970s, which is assumed to be related to a climatic shift (Giese et. al., 2002). The comparison between the PDO index and Vostok isotope data since 1650 suggests that five climate shifts have occurred in the last three centuries. During the study period, Vostok summer temperature varied with a period of 30–50 years and with a magnitude of ~3.5º C. In the 18th and 19th Centuries the temperature decreased, and the 20th Century is characterized by a positive trend.

- In 2014 the Antarctic ozone hole reached its annual peak size on 11 September according to scientists from NASA and the National Oceanic and Atmospheric Administration. On that day the size of the ozone hole was 24.1 million square kilometres, which is an area roughly the size of North America. During August and September it was generally similar in size to the ozone hole of 2013, and mostly smaller than the decadal mean. It is estimated that it will be several decades before Antarctic stratospheric ozone concentrations in the spring return to pre-ozone-hole levels.

- Since the 1950s surface air temperatures have risen significantly at many of the stations on the Antarctic Peninsula, although warming has slowed markedly over the last decade. Nevertheless, on 24 March 2015, a temperature of +17.5ºC was recorded at Esperanza station in the northern part of the Peninsula. This exceeded the previous maximum temperature recorded at the same station (+17.1ºC on 24 April 1961) and is the highest temperature ever recorded on the Antarctic continent. The extreme temperature was associated with an unusual combination of weather events, with warm subtropical air being drawn southwards and then forced over the mountains of the Peninsula, warming further through the Föhn effect as it descended towards Esperanza.

- Li et al. (2014) investigated the changes in sea ice between the Antarctic Peninsula and the Ross Sea over recent decades. They proposed that tropical SSTs in the Atlantic related to the Atlantic Multi-decadal Oscillation established a wave train to the Amundsen Sea and contributed to the dipole-like sea ice redistribution between the Ross Sea area and the Amundsen – Bellingshausen Seas. The loss of sea ice over the Bellingshausen Sea was linked to the warming of the Antarctic Peninsula. Strong links to the tropical Atlantic were similarly identified by Simpkins et al. (2014).

- Antarctic sea ice continued to increase in extent, in June 2014 reaching an anomaly of some 2.074 million square kilometres above the long term average, and surpassing a winter record of 19.44 million square kilometres from 2012 (according to NSIDC), at the same time as the Southern Ocean continued to warm. NSIDC reports that Antarctic sea ice has been growing at about 2.6% per decade. There are various theories as to why the ice extent has increased, including freshwater injection from melting ice from West Antarctica, stronger southerly winds in the Ross Sea caused by the ozone hole, lower sea surface temperatures (Fan et al. 2014) and feedbacks involving the atmosphere and ocean. Ferreira et al. (2015) suggested that, in particular, a short timescale response of increasing sea ice as a result of strengthening westerlies is a possible mechanism (on timescales of up to ~20 years), but that the simulated longer-term response is decreasing sea ice.

- Fan et al. (2014) suggested that there were colder conditions and the possibility of greater sea ice extents before the start of the modern satellite era in 1979. That is backed up by recent reconstructions of recovered early satellite imagery, which indicates that in the early 1960s Antarctic sea ice could have been more extensive than at present (Gallaher et al. 2014). The sea ice is now reported to be thicker than had been expected from previous analyses. Use of under-ice vehicles shows that near the coast sea ice drafts range from 1.4 to 5.5 m, with maxima up to 16 m (Williams et al. 2015). The lack of under-ice vehicle measurements in previous years precludes accurate estimates of any change in thickness with time.

- An analysis of satellite radar altimeter observations has shown that the loss of ice from ice shelves around Antarctica changed from near negligible in 1994-2003 (25±64 km^3/yr) to rapid in 2003-2012 (310±74 km^3) (Paolo et al. 2015). An earlier slight gain of ice shelves around East Antarctica ceased, while losses from ice shelves around West Antarctica increased by 70%. Some ice shelves in the Amundsen Sea and Bellingshausen Sea have lost up to 18% of their thickness in less than 2 decades. Thinning of the ice shelves removes their buttressing effect, allowing ice streams from the interior to move faster towards the coast, leading to an increase in iceberg discharge and loss of ice from the interior. If this acceleration continues we face potential destabilisation and collapse of parts of the West Antarctic ice sheet. These findings are corroborated by McMillan et al. (2014), who used 3 years of Cryosat-2 data to show losses of 134±27 Gt/yr from West Antarctica, 3±36 GT/yr from East Antarctica, and 23±18 Gt/yr from the Antarctic Peninsula between 2010 and 2013. Mass losses from West Antarctica are now 31% greater than in 2005-2010. These findings are consistent with the observation that the grounding lines of the Pine Island and associated glaciers have retreated significantly in recent years (Rignot et al. 2014). The present ice configuration is deemed unstable. Rignot et al. (2014) concluded "that this sector of West Antarctica is undergoing a marine ice sheet instability that will significantly contribute to sea level rise in decades to centuries to come". It has been suggested that the melting of these ice shelves from beneath is a function of the southward shift in westerly winds (Spence et al. 2014).

- Analyses of global sea level show it continuing to rise at a rate of 3±0.7 mm/yr between 1993 and 2010, which is an increase of 1.2±0.2 mm/yr between 1901-1990 (Hay et al. 2015). The acceleration is most likely to reflect a combination of warming (i.e. expansion) of ocean water, and loss of ice from ice sheets and from mountain glaciers, in roughly equal proportions.

- de Lavergne et al. (2014) have shown that the melting of ice shelves has considerably enhanced the salinity stratification of the coastal ocean around Antarctica. This surface freshening has likely weakened the deep convection in the Weddell Sea, slowing the production of Antarctic Bottom Water.

- Totten Glacier has the largest thinning rate in East Antarctica. Recently a trough has been found beneath the glacier through which warm subsurface waters could reach to destabilize the ice of the Aurora Subglacial Basin. Draining the ice from this region could raise global sea level by 3.5 m (Greenbaum et al. 2015).

- Modeling studies have suggested that warming of the Southern Ocean and Antarctica will accelerate through the 21st Century, with increased heating via the ocean from below, and via the atmosphere from above, which should lead to a decline in sea ice area (Liu and Curry 2010). The regional pattern of sea ice change is highly variable between models. Changes in local winds are thought to be responsible.

Changes in the Antarctic biological environment

- A continent-wide analysis of emperor penguin populations indicates that at least 75% of colonies are vulnerable to future low sea ice concentration, and 20% will probably be quasi-extinct by 2100. The global population is expected to decline by at least 19% after a phase of slight increase until 2050. The reasons are complex. Deviations from optimum sea-ice conditions reduce survival of adults due to poor food availability, lower the breeding success and diminish chick feeding rates (Jenouvrier et al. 2014). Climate-mediated impacts are also predicted in Adélie penguin populations (Ballerina et al. 2015) and Ropert-Coudert et al. (2014) recently documented the breeding failure of an entire Adélie colony in response to unusual and extreme weather events.

- An assessment of environmental changes with a possible impact on the marine ecosystem in the Southern Ocean shows: (i) large proportions of the Southern Ocean are and will be affected by one or more climate change processes; areas that will be affected in the future are larger than those that are already under environmental stress, (ii) areas affected by sea-ice changes in the past and also in the future are larger than areas that experience ocean warming, (iii) pelagic marine habitats are likely to become warmer and fresher, with strengthening westerly winds and an increase in ocean eddy activity (Constable et al. 2015; Gutt et al. 2015). Lower trophic levels are likely to move south in the pelagic environment as their optimal habitats move polewards.

- Aragonite undersaturation (ocean acidification) might become (in terms of area affected) one of the biggest challenges for the Antarctic marine ecosystem in future decades. Direct and indirect impacts of various environmental changes to the three major habitats (sea-ice, pelagic and benthos and their biota) are shown to be complex, and most of them are assumed to be non-linear. Areas affected by environmental stressors range from 33% of the Southern Ocean for a single stressor, to <1% for four and five overlapping factors. In the future, areas expected to be affected by two and three overlapping factors are equally large, and together cover almost 86% of the Southern Ocean ecosystem (Constable et al 2015; Gutt et al. 2015).

- The vulnerability of Antarctic shallow water habitats to climate change was highlighted by Clark et al. 2015. These unique, invertebrate dominated systems mostly consist of dark-adapted species, and rely on sea-ice to maintain theses low-light environments. As sea-ice changes it is predicted that some of these communities are at risk from climate mediated collapse, with a regime shift to algae dominated assemblages.

- Primary production (growth of microalgae) in open water areas west of the Antarctic Peninsula increased from 0.73 to 1.03 Tg C yr^{-1} between 1997 and 2010. These findings result from analyses of time series measurements of physical variables as well as biological parameters, and from a photosynthesis and photo-inhibition model. This overall increase in primary production was mainly caused by the increase in the length of the production season as well as ocean warming. Photo-inhibition due to the temporal coincidence of climate-change induced earlier sea ice retreat and the presence of the ozone hole had less effect (Moreau et al. 2015).

- Terrestrial mosses from across Antarctica are responding to climate change with changes in growth rates and stable isotope proxies. Across a 1,500 km environmental gradient from the maritime Antarctic (Signy Island) to the southern Antarctic Peninsula (Lazarev Bay, Alexander Island) moss bank accumulation rates started to increase from around 1950, reaching peaks at Lazarev Bay in the 1970s (briefly over 0.1 g of dry matter (DM) cm^{-2} yr^{-1}) and Signy Island in the 1990s (0.06 g DM cm^{-2} yr^{-1}); the most recent measurements are similar at around 0.04 g DM cm^{-2}. In continental Antarctica, moss growth rates are inversely proportional to summer wind speed, and proportional to the number of days above 0°C and to summer temperature. Windmill Island mosses had maximum growth rates in the 1950s - 1980s that subsequently fell in the 1990s and 2000s. At the Vestfold Hills the most recent moss growth rates have been highest (Clarke et al., 2012). The length of the growing season has been identified as a critical determinant of moss growth rate in both continental and AP locations (Royles et al., 2015).

- Until recently the Antarctic continent and Peninsula have been little impacted by non-native species, compared to other regions of the Earth. However, reports of species introductions are increasing as awareness of biological invasions as a major conservation threat, within the context of increased human activities and climate change scenarios, has grown within the Antarctic science community. Given the recent increase in documented reports, Hughes et al. (2015) created an up-to-date inventory of known terrestrial non-native species introductions, including those subsequently removed since the 1990s, within the Antarctic Treaty area. Reports of non-native species established in the natural environment are mainly located within the Antarctic Peninsula region and Scotia Arc, with Deception Island, and more generally the South Shetland Islands, the most impacted areas.

- Climate amelioration is likely to facilitate the influx of non-native soil organisms and promote landscape-scale changes to biodiversity (Neilsen & Wall 2013). These authors also predict that in addition to direct effects of a changing climate, Antarctic soil invertebrate communities will be affected by climate mediated changes in vegetation and changes in microbial community composition.

- A novel means of cryptobiotic survival *in situ* in the Antarctic over periods of centuries to millennia has been reported in studies of regeneration from within deep Antarctic moss bank cores (Roads et al. 2014). These banks, some of which are known to have maximum basal ages of 5-6 ky, are a characteristic feature of Antarctic Peninsula and Scotia Arc vegetation, and consist of moss that grows continuously from the surface, with previous years' growth becoming rapidly preserved in the underlying permafrost. Roads et al.'s (2014) study demonstrated viability at an age in the profile of c. 1600 years before present (ybp), sufficient to permit survival through short- to middle-term ice advances such as might occur during the Little Ice Age. The potential for much longer survival exists but has not been demonstrated.

- Suckling et al. (2014) examined the effects of long-term culture under altered conditions on the Antarctic sea urchin, *Sterechinus neumayeri*. They considered combined environmental stressors of lowered pH (-0.3 and -0.5 pH units) and increased temperature (+2°C) for 2 y, which covered two full reproductive cycles in this species. Adults took at least 6–8 months to acclimate to the altered conditions, but beyond this, there was no detectable effect of temperature or pH. These data show that, under long-term culture, adult *S. neumayeri* appear to acclimate their metabolic and reproductive physiology to the combined stressors of altered pH and increased temperature, with relatively little measureable effect.

- Agostini et al. (2015) investigated the population structure of *Pleuragramma antarctica* along the Antarctic Peninsula. This fish has a major trophic role as krill predator and as prey for penguins and seals, and needs sea ice for reproduction. The resilience of krill and *P. antarctica* to current warming and sea-ice decline appears based on migration, which in turn is producing precipitous decline of Adélie penguins, e.g. at Palmer Station (Emslie et al., 1998; Moline et al., 2008; Ducklow et al., 2012).

The SCAR ACCE Advisory Group consists of John Turner (Chair), Colin Summerhayes, Mike Sparrow, Paul Mayewski, Pete Convey, Guido di Prisco, Julian Gutt , Dominic Hodgson, Sabrina Speich, Tony Worby, Sun Bo and Alexander Klepikov.

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